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David Bliss, David Weyburne, *P. S. Kuo, *K. L. Vodopyanov, *M. M. Fejer, **X. Yu, **J. S. Harris

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Optoelectronic Technology Branch, AFRL/RYHC, 80 Scott Drive, Hanscom AFB, MA 01731; *E. L. Ginzton Laboratory, Stanford University, Stanford, CT 94305; **Solid State Photonics Laboratory, Stanford University, Stanford, CT 94305

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14. ABSTRACT

We demonstrate an optical parametric oscillator (OPO) based on GaAs pumped with linearly polarized and circularly polarized light and show that the relative OPO thresholds agree with theoretical expectations. For the circularly polarized pump, the threshold was as low as for the [111]-linearly polarized pump case. The pump was also passed through a Lyot depolarizer to produce pseudo-depolarized light, and the OPO threshold in this case was only 22% higher than that for [001]-linearly polarized pump.

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GaAs optical parametric oscillator with circularly polarized and depolarized pump

P. S. Kuo,[1,*] K. L. Vodopyanov,[1] M. M. Fejer,[1] X. Yu,[2] J. S. Harris,[2] D. F. Bliss,[3] and D. Weyburne[3]

[1]E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA
[2]Solid State Photonics Laboratory, Stanford University, Stanford, California 94305, USA
[3]Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts 01731, USA
*Corresponding author: pskuo@stanford.edu

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We demonstrate an optical parametric oscillator (OPO) based on GaAs pumped with linearly polarized and circularly polarized light and show that the relative OPO thresholds agree with theoretical expectations. For the circularly polarized pump, the threshold was as low as for the [111]-linearly polarized pump case. The pump was also passed through a Lyot depolarizer to produce pseudo-depolarized light, and the OPO threshold in this case was only 22% higher than that for [001]-linearly polarized pump. © 2007 Optical Society of America

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There is growing interest in gallium arsenide (GaAs) for use as an infrared nonlinear optical crystal because of its large nonlinear susceptibility ($d_{14}=94$ pm/V for frequency doubling of $\lambda_f=4$ μm [1]) and broad infrared transparency range ($\lambda=0.9$–17 μm). The nonlinear susceptibility tensor of GaAs and related $\bar{4}3m$ zinc blende materials is highly symmetric; the only nonzero tensor elements are d_{xyz} and its permutations ($d_{xyz}=d_{14}=d_{25}=d_{36}$ in contracted notation). This property, together with isotropy in refractive index, leads to interesting polarization combinations of the three interacting waves. Use of GaAs as an efficient nonlinear optical material has been enabled by the development of fabrication and growth technologies to achieve quasi-phase-matching (QPM) in GaAs. Orientation-patterned GaAs (OP-GaAs) is a type of QPM GaAs in which periodic inversions of the crystallographic orientation are grown into the material. The growth of OP-GaAs involves molecular beam epitaxy, lithographic definition of QPM periods, and hydride vapor phase epitaxy [2–5].

The polarization dependence of three-frequency processes in QPM GaAs has been explored in several previous experiments. Vodopyanov *et al.* [6] demonstrated pumping of an OP-GaAs optical parametric oscillator (OPO) with various linear polarizations. A similar experiment was performed showing optical parametric generation in OP-GaAs with circularly polarized and several different linearly polarized pumps [7,8]. Perrett *et al.* [9] have explored optical parametric amplification in glass-bonded QPM GaAs. In this Letter, we report quantitative studies of the dependence of the threshold of an OP-GaAs OPO on polarization and also the first demonstration (to our knowledge) of an OPO pumped with circularly polarized and depolarized light.

In OP-GaAs samples, the beams propagate along the $[\bar{1}10]$ crystallographic direction, and the electric fields of the interacting waves all lie in the plane containing [001], [110], and [111] [see Fig. 1(a)]. We can calculate the gain associated with a polarization combination by considering the effective nonlinear coefficient, d_{eff}. For given pump and signal fields, the nonlinear polarization, $\vec{P}^{\text{NL}}$, at the idler is given by [10]

$$P_i^{\text{NL}}(\omega_1) = 2\epsilon_0 \sum_{jk} d_{ijk} E_j^*(\omega_2) E_k(\omega_3), \tag{1}$$

where the idler, signal, and pump frequencies are ω_1, ω_2, and ω_3, respectively, and $\omega_3=\omega_1+\omega_2$. If the component of $\vec{P}^{\text{NL}}$ that excites a propagating idler wave is denoted $\vec{P}^{\text{NL}}(\omega_1,\text{prop})$, then d_{eff} is defined by the equation

$$|\vec{P}_i^{\text{NL}}(\omega_1,\text{prop})| = 2\epsilon_0 d_{\text{eff}} |\vec{E}(\omega_2)||\vec{E}(\omega_3)|. \tag{2}$$

The small-signal parametric gain is proportional to d_{eff}^2. We can calculate the magnitude of the effective nonlinear coefficient for different pump polarizations based on the assumption that the OP-GaAs OPO will oscillate with the signal polarization that maximizes the parametric gain. The calculation also gives the preferred polarizations for the signal and idler. Figure 1(b) plots d_{eff}^2 as a function of the angle to the [110] direction of a linearly polarized pump. Note

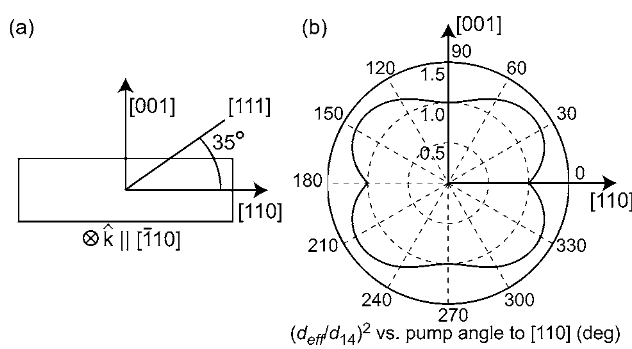

Fig. 1. (a) Sketch of the propagation geometry in OP-GaAs and several key crystallographic directions. (b) Relative gain, expressed as $(d_{\text{eff}}/d_{14})^2$, as a function of angle to the [110] direction for a linearly polarized pump.

that for a quasi-phase-matched interaction, d_{eff} is reduced by a factor of $2/\pi$.

It is worthwhile to describe a few polarization combinations in greater detail (summarized in Table 1). When the pump is linearly polarized along [001], both signal and idler are linearly polarized along [110] and $d_{\text{eff}}=d_{14}$. When the pump is along [111] (35° to the [110] direction), the signal and idler waves are both parallel to the pump, and d_{eff} is maximized [see Fig. 1(b)] with a value of $2d_{14}/\sqrt{3}=1.155d_{14}$. When the pump wave is polarized in the [110] direction, $d_{\text{eff}}=d_{14}$ for all signal polarizations, so long as the idler is complementarily polarized to the signal. In this special case, it is theoretically possible to amplify or oscillate an arbitrarily polarized signal wave in GaAs. A polarization-insensitive amplifier has intriguing applications for WDM networks [11] and photon-counting detectors. In practice, an OPO with a randomly polarized signal may be difficult, since birefringence, polarization-dependent loss, or other asymmetries can cause well-defined polarization eigenmodes in the OPO cavity. Since the indices in the nonlinear tensor can be permuted, we infer that for an OP-GaAs OPO pumped with unpolarized light, $d_{\text{eff}}=d_{14}$, and the resonated signal will be [110] polarized with the idler complementarily polarized to the pump. Finally, an OPO with a circularly polarized pump will have $d_{\text{eff}}=d_{14}(1+\sqrt{5})/(2\sqrt{2})=1.144d_{14}$, nearly as large as for pumping with [111]-linearly polarized light. For this case, both the signal and the idler are elliptically polarized with their major axis along [110] and ellipticity (ratio of major to minor axes of the electric fields [12]) of $(1+\sqrt{5})/2$, the golden ratio. Also, the signal and idler will have the same handedness, opposite to that of the pump.

The experimental setup for the OP-GaAs OPO is sketched in Fig. 2. The OP-GaAs sample was 11 mm long, 6 mm wide, and 600 μm thick with a 130 μm QPM period and was pumped with 2.79 μm wavelength, 26 ns duration pulses with energy up to 65 μJ from a periodically poled $LiNbO_3$ (PPLN) OPO that was in turn pumped with a Q-switched, 1.064 μm Nd:YAG laser (Spectra-Physics X30-106Q laser at a 100 Hz repetition rate). The spectral linewidth of the PPLN OPO was narrowed with an intracavity, 40 μm thick YAG etalon to 6 nm FWHM to better match the pump acceptance bandwidth of the OP-GaAs OPO. After filtering out the shorter wavelengths produced by the PPLN OPO, the linearly polarized 2.79 μm pulses were attenuated with a pair of GaAs Brewster plates and then focused to a 125 μm $1/e^2$-intensity radius spot. The pump was double passed in the OP-GaAs OPO, whose cavity consisted of a metal mirror (500 mm radius of curvature) and a flat dielectric mirror that reflected the 4.8 μm signal and transmitted the pump and 6.7 μm idler. A dielectric beam splitter separated the pump from the signal and idler waves. The OP-GaAs crystal had broadband antireflection coatings ($R<1\%$ at the signal, $R<3\%$ at the idler, and $R\approx 20\%$ at the pump). The output of the OP-GaAs OPO was detected with an amplified pyroelectric detector preceded by a 4 μm cutoff long-pass filter.

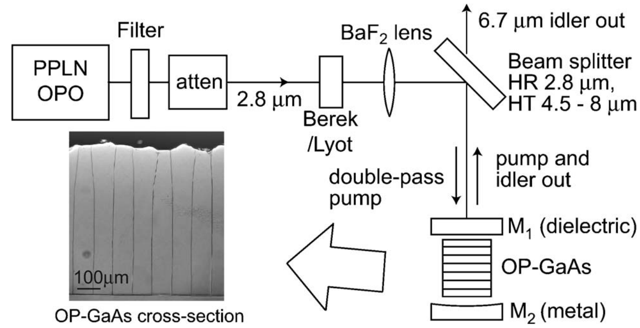

Fig. 2. Experimental setup for the OP-GaAs OPO.

To change the orientation of the linear pump polarizations relative to the OP-GaAs crystal, the sample was rotated in the pump beam. A quarter-wave plate, formed by a MgF_2 Berek compensator (New Focus Model 5540), was used to convert linearly polarized pulses from the PPLN OPO to circular polarization. To produce pseudo-depolarized pulses, the output of the PPLN OPO was passed through a Lyot depolarizer consisting of a 75 mm long $LiNbO_3$ crystal oriented such that the light propagated with k vector orthogonal to the z axis and polarization at 45° to the z axis. The $LiNbO_3$ crystal was sufficiently long such that the group delay between the two principal polarizations was much larger than the coherence time of the pump pulses, which effectively scrambled the polarization of the light [13]. To avoid the need to refocus the pump, the $LiNbO_3$ crystal was left in the pump beam throughout the experiment and simply rotated between 0° and 45° to pass linearly polarized or produce pseudo-depolarized light.

Figure 3 plots the energy curves for [001]-, [110]-, [111]-linearly and circularly polarized pumps. From these curves, we estimated the threshold for the [111]-linearly polarized pump to be at 30 μJ while the thresholds for both the [001]- and [110]-linearly polarized pumps were at 41 μJ. The observations of identical thresholds for the [001]- and [110]-polarized cases and that the [111]-polarized pump threshold energy was 3/4 the size of the [001]-polarized case agree very well with theory, since the OPO threshold energy is proportional to $1/\text{gain} \propto 1/d_{\text{eff}}^2$. The thresh-

Table 1. Expected OPO Outputs and Associated Effective Nonlinear Coefficients for Several Pump Polarizations

Pump Polarization	Signal Polarization	Idler Polarization	d_{eff}
[001]-linearly polarized			d_{14}
[111]-linearly polarized			$\frac{2}{\sqrt{3}}d_{14}$
[110]-linearly polarized	Arbitrarily polarized signal	Idler complementary to signal	d_{14}
Circularly polarized			$\frac{1+\sqrt{5}}{2\sqrt{2}}d_{14}$

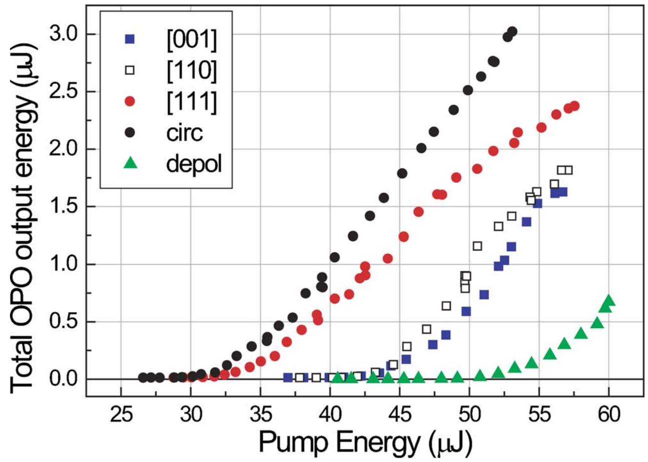

Fig. 3. (Color online) OP-GaAs OPO energy curves for [001]-, [110]-, and [111]-linearly polarized pumps, as well as circularly polarized and pseudo-depolarized pumps.

old for the circularly polarized pump was about 29 μJ, which was slightly lower than the threshold for the [111]-linearly polarized pump. Theory predicts the circularly polarized pump to have slightly higher threshold than the [111]-linearly polarized case; the discrepancy may be attributed to uncertainty in alignment of the linearly polarized pump to the [111] direction.

The OPO energy curve for the pseudo-depolarized pump is also plotted in Fig. 3. We observed the threshold for the depolarized pump at 50 μJ, which was only 22% higher than the threshold for the [001]-linearly polarized pump and only 67% larger than the [111]-polarized case. Also, at 55 μJ of pump energy (10% above threshold), we observed parametric oscillation for every pump pulse. Since the threshold for the depolarized pump is less than twice larger than that for the linearly polarized pump cases, we conclude that this is the first OPO to be pumped in a nontrivial way with a depolarized source. We note that the threshold for the depolarized pump was not as low as for the [001]-linearly polarized pump (as was hypothesized); further studies are needed to understand this difference.

Using an IR wire grid polarizer, we performed a rough characterization of the OPO output polarizations. The observed signal and idler polarizations were slightly different from the polarizations predicted by theory, which we believe is due to the small amount of strain-induced birefringence in this particular OP-GaAs sample. The birefringence affects the polarization eigenmodes of the OPO cavity and will change the polarization of the nonresonant idler wave. Detailed analyses of the polarization states of the birefringent cavity are beyond the scope of this Letter. We expect future OP-GaAs samples to have less birefringence.

These results demonstrate some of the diverse polarization combinations offered by GaAs and related zinc blende nonlinear optical crystals such as GaP and ZnSe. We demonstrated pumping of an OP-GaAs OPO with both circularly polarized and pseudo-depolarized light. The experiment showed that the circularly polarized pump case had a threshold as low as the best linearly polarized case. Also, the threshold for the pseudo-depolarized pump case was only 22% larger than the [001]-linearly polarized pump case. Inclusion of circularly polarized and depolarized waves in $\chi^{(2)}$-nonlinear optics opens up new operating regimes for devices previously accessible only by linearly polarized light.

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